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ORIGINAL ARTICLE

Torsion biomechanics of the spine following lumbar laminectomy: a human cadaver study

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Abstract

Purpose Lumbar laminectomy affects spinal stability in shear loading. However, the effects of laminectomy on torsion biomechanics are unknown. The purpose of this study was to investigate the effect of laminectomy on torsion stiffness and torsion strength of lumbar spinal segments following laminectomy and whether these biomechanical parameters are affected by disc degeneration and bone mineral density (BMD).

Methods Ten human cadaveric lumbar spines were obtained (age 75.5, range 59–88). Disc degeneration (MRI) and BMD (DXA) were assessed. Disc degeneration was classified according to Pfirrmann and dichotomized in mild or severe. BMD was defined as high BMD ($\geq$median BMD) or low BMD ($<$median BMD). Laminectomy was performed either on L2 ($5\times$) or L4 ($5\times$). Twenty motion segments (L2–L3 and L4–L5) were isolated. The effects of laminectomy, disc degeneration and BMD on torsion stiffness (TS) and torsion moments to failure (TMF) were studied.

Results Load–displacement curves showed a typical bi-phasic pattern with an early torsion stiffness (ETS), late torsion stiffness (LTS) and a TMF. Following laminectomy, ETS decreased 34.1 % ($p < 0.001$), LTS decreased 30.1 % ($p = 0.027$) and TMF decreased 17.6 % ($p = 0.041$). Disc degeneration ($p < 0.001$) and its interaction with laminectomy ($p < 0.031$) did significantly affect ETS. In the mildly degenerated group, ETS decreased 19.7 % from 7.6 Nm/degree (6.4–8.4) to 6.1 Nm/degree (1.5–10.3) following laminectomy. In the severely degenerated group, ETS decreased 22.3 % from 12.1 Nm/degree (4.6–21.9) to 9.4 Nm/degree (5.6–14.3) following laminectomy. In segments with low BMD, TMF was 40.7 % ($p < 0.001$) lower than segments with high BMD [34.9 Nm (range 23.7–51.2) versus 58.9 Nm (range 43.8–79.2)].

Conclusions Laminectomy affects both torsion stiffness and torsion load to failure. In addition, torsional strength is strongly affected by BMD whereas disc degeneration affects torsional stiffness. Assessment of disc degeneration and BMD pre-operatively improves the understanding of the biomechanical effects of a lumbar laminectomy.

Keywords Laminectomy · Human lumbar spine · Torsion stiffness · Torsion strength · Disc degeneration · Bone mineral density

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Introduction

Symptomatic lumbar spinal stenosis is a common degenerative disorder in the aging population. It can lead to low back pain and radiculopathy, neurogenic claudication and muscle weakness. Spinal decompression by facet joints preserving laminectomy of the affected lumbar segment is a commonly used surgical technique to alleviate symptoms. However, a decompression laminectomy obviously leads to a loss of anatomical integrity due to the removal of bony structures and the interspinous, posterior longitudinal and flavum ligaments. Despite preservation of the facet joints, lumbar laminectomy may affect spinal biomechanics, causing return of symptoms due to rotatory slips, degenerative scoliosis and post-operative fractures which are defined as post-laminectomy syndrome or failed back surgery syndrome.

The effect of lumbar laminectomy on intervertebral shear stiffness and shear force to failure is well-known [5, 6]. However, during daily activities such as asymmetric lifting [17], the lumbar spine is not only subjected to shear forces but also to torsion moments and the resulting axial rotation. Torsional injuries of the lumbar spine occur with load application accompanied by axial rotation [1, 10]. It is commonly held that a decreased resistance to spinal torsion is one of the most important parameters in the etiology of low back pain and disc degeneration [4, 11, 12].

In the present study, the effects of laminectomy on the torsion stiffness (TS) and torsion strength expressed as torsion moment to failure (TMF) are quantified in 20 human cadaveric lumbar spinal segments. In addition, it was also assessed whether the severity of disc degeneration and differences in bone mineral density (BMD) of the lumbar spine interact with laminectomy with respect to stiffness and failure moment.

We hypothesized that laminectomy substantially reduces TS and TMF of the human lumbar spine, and that the severity of disc degeneration and low BMD independently influence the post-operative biomechanical properties, expressed by TS and TMF, following laminectomy.

Methods

Specimens and specimen preparation

Thoracolumbar spines (T12–L5) were harvested from freshly frozen (−20 °C) human cadavers (mean age 75.5 years, range 59–88 years). None of the donors had any history of spinal injury, surgery or metastatic disease. The spines were thawed before testing. Excessive soft tissue and muscle tissue were removed, keeping the anterior and posterior longitudinal ligaments and facet joints intact. Lumbar spines were sectioned in an L2–L3 and an L4–L5 segment. To exclude systematic effects of segment level, laminectomy was performed at L2 or L4 in a balanced design. The untreated level of each thoracolumbar spine was considered as internal control. Laminectomy, analogous to standard clinical practice, was performed by removing the spinous process and attached part of the lamina and the flavum and interspinous ligaments, leaving the facet joints intact.

During preparation, assessment and biomechanical testing, specimens were kept hydrated using 0.9 % saline-soaked gauzes. Furthermore, anteroposterior, lateral and oblique radiographs (Sedical© Digital Vet. DX-6, Arlington Heights, IL, USA) were made to determine whether bridging osteophytes were present in segments. Thoracolumbar spines with bridging osteophytes were excluded.

Before sectioning spines in segments for testing, MRI (Siemens© Symphony 1.5 Tesla: Syngo MR A30, software NUMARIS/4, Berlin, Germany) of the intact lumbar spines was performed to assess disc degeneration. Degeneration of the L2–L3 and L4–L5 intervertebral discs was graded according to the Pfirrmann classification of T2-weighted mid-sagittal sections [18]. Subsequently, degeneration scores were dichotomized; grades 3 or lower were classified as ‘mildly degenerated’ while grades higher than 3 were classified as ‘severely degenerated’.

BMD (g/cm^2) of each lumbar spine was determined at L1–L4 with dual X-ray absorptiometry (DXA, Hologic© QDR 4500 Delphi DXA scanner, Waltham, MA, USA) in anteroposterior direction, in accordance with common clinical practice. Low BMD was defined as lower than median, while high BMD was defined as median or higher.

After sectioning spines into L2–L3 and L4–L5 segments, the motion segments were potted in a casting mold using low melting point (48 °C) bismuth alloy (Cerrolow-147; 48.0 % bismuth, 25.6 % lead, 12.0 % tin, 9.6 % Cadmium and 4.0 % indium). The disc was placed parallel to the flat surface of the bismuth based on visual inspection. The upper and lower vertebral bodies were fixed securely into the alloy by adding screws into the vertebral body. Screw fixation was reinforced with orthopedic bone cement (Stryker©, Simplex, Kalamazoo, MI, USA). All articulating parts were kept free.

Biomechanical testing

The casting mold was placed in a hydraulic materials testing machine (Instron©, model 8872; Instron and IST, Norwood, Canada), to apply torsion moments. Spinal segments were tested without imposing a specific axis of axial rotation in a custom-made test setup (Fig. 1). Consequently, segments were able to find their physiological motion patterns irrespective of possible differences in embedding. During application of torsion moments, segments were loaded with a continuous purely axial compressive force of 1,600 N applied using a pneumatic cylinder [5, 6]. Calibration of axial compression was performed using a load cell (Hottinger Baldwin Messtechnik©, Force Transducer Type C2, Darmstadt, Germany). The 1,600 N preload was selected to allow for comparison with

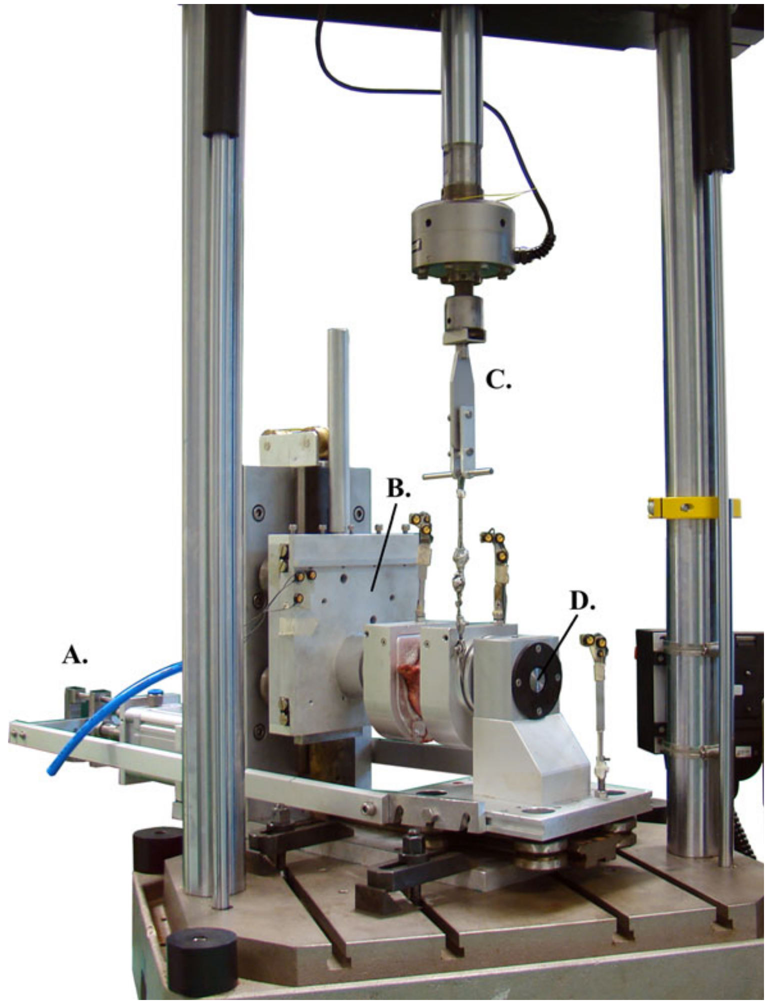

Fig. 1 Segment placed in the materials testing machine, showing the pneumatic cylinder used to apply axial compression (*A*), the free center of rotation (*B*), vertical load transfer through a metal wire inducing axial rotation (*C*) and finally the fixed center of rotation (*D*)

load levels found in daily physiological loading [16] and to compare with previous work [5, 6], without causing compressive failure [7]. Subsequently, torsion load was applied with a constant rate of 3.0° per min by pulling on a metal wire, which was securely fixed to the part of the casting mold that contained the caudal vertebral body (Fig. 1). The test was stopped after hearing a clear crack or after a large moment reduction was seen. Torsion moment and displacement were recorded and digitized at 100 Hz (Instron© Fast Track 2).

For each of the 20 motion segments tested, TMF was determined. The TMF was defined as the maximum moment (in Newton meter) recorded. The torsion stiffness was calculated from the load–displacement curve. Load–displacement curves showed two distinct phases with differences in stiffness in the early and late phase of the curve. The transition phase between the early and late phase of the load–displacement curve indicated gradual yielding. Therefore, stiffness was analyzed separately for the early and late phase. Early torsion stiffness (ETS) was calculated between 20.0 and 40.0 % of the TMF, while late torsion stiffness (LTS) was calculated between 60.0 and 80.0 % of the TMF. TS was estimated by means of a least squares fit of a straight line through the torsion load–displacement data with the slope of the fitted line representing stiffness. The deformation in this region was linear between load and displacement for all motion segments. r^2 values were all above 0.96 except for 4 individual values (Table 1). We checked these curves visually and found that a linear fit was optimal and that the lower r^2 values were caused by minor irregularities in the curves rather than clear non-linearities.

Statistical methods

ANOVA was used to assess relationships between dependent and independent variables. Dependent variables were ETS, LTS and TMF. First, analyses were performed to determine the effect of laminectomy and degeneration on all three dependent variables, using laminectomy and dichotomized Pfirrmann scores as fixed factors and specimen as random factor. Next, we tested whether dichotomized BMD co-determined independent variables and whether these modified the effects

Table 1 Specimens; independent and dependent variables per segment

	Segment	Independent variables			Dependent variables		
		Laminectomy (0/1)	Disc degeneration (Pfirrmann) (1-5)	Total bone mineral density of L1-L4 (BMD) (g/cm^2)	Early torsion stiffness (ETS) (Nm/degree)	Late torsion stiffness (LTS) (Nm/degree)	Torsion moment to failure (TMF) (Nm)
Specimen 01	L2–L3	0	4	1.13	9.4 (0.998)	0.6 (0.854)	44.8
Male, 79	L4–L5	1	3		9.6 (0.442)	7.2 (0.986)	45.8
Specimen 02	L2–L3	0	4	0.64	4.6 (0.999)	0.6 (0.976)	38.2
Male, 70	L4–L5	1	3		6.5 (0.998)	0.9 (0.919)	35.2
Specimen 03	L2–L3	0	4	1.05	9.0 (0.989)	7.9 (0.998)	56.5
Male, 65	L4–L5	1	2		10.3 (0.997)	7.0 (0.998)	63.5
Specimen 04	L2–L3	0	5	0.92	21.9 (0.997)	16.3 (1.000)	68.2
Male, 73	L4–L5	1	5		14.3 (1.000)	8.5 (0.995)	72.5
Specimen 05	L2–L3	0	4	0.70	18.2 (0.997)	9.8 (0.992)	46.9
Female, 83	L4–L5	1	5		8.2 (1.000)	3.6 (0.998)	29.8
Specimen 06	L2–L3	1	3	0.69	1.8 (0.997)	1.9 (0.999)	23.7
Female, 83	L4–L5	0	3		7.9 (0.998)	3.4 (0.999)	45.0
Specimen 07	L2–L3	1	2	0.81	3.7 (0.980)	1.2 (0.998)	43.8
Male, 59	L4–L5	0	3		8.4 (0.997)	1.0 (0.991)	56.1
Specimen 08	L2–L3	1	3	0.89	9.3 (0.999)	5.6 (0.998)	58.3
Female, 84	L4–L5	0	4		9.6 (0.986)	8.3 (0.998)	79.2
Specimen 09	L2–L3	1	3	0.55	1.5 (0.716)	0.8 (0.989)	24.0
Male, 71	L4–L5	0	3		6.4 (1.000)	2.9 (0.960)	27.8
Specimen 10	L2–L3	1	4	0.68	5.6 (0.999)	3.3 (0.995)	26.9
Male, 88	L4–L5	0	4		12.1 (0.997)	6.4 (0.996)	51.2

For early and late torsion stiffness, respectively, ETS and LTS, r^2 values are added in brackets

0, untreated; 1, laminectomy

of laminectomy, by repeating the analysis while replacing the factor dichotomized Pfirrmann score by the dichotomized BMD in the ANOVA. Note, however, that in the latter test, specimen could not be maintained as a random factor as BMD only varied between and not within segments. Consequently, this test was less sensitive for detecting effects of laminectomy, and therefore, main effects of laminectomy are not presented for this test. A significance level of 5 % was used. The statistical analyses were performed using SPSS for Mac version 16.0 (SPSS Incorporated©, Chicago, IL, USA).

Results

All specimen parameters and outcome measures are presented in Table 1. Visual inspection and MRI confirmed that facet joints were intact, and no fractures of the pars interarticularis were present in operated or intact segments before mechanical testing. Ten segments were classified as mildly degenerated and ten segments as severely degenerated. The median total BMD of all spines (L1–L4) was 0.76 g/cm^2 (range 0.55–1.13). Therefore, low BMD was defined as <0.76 g/cm^2 and high BMD was defined as ≥0.76 g/cm^2. Furthermore, a significant difference ($p < 0.001$) between mean ETS (8.9 ± 5.0) and mean LTS (4.9 ± 4.1) was found using a paired t test. In some load–displacement curves, a clear yield point was seen, whereas in other, there was a gradual decline in stiffness.

Effects of laminectomy on torsion biomechanics

Figure 2a presents a typical example of our data. Following laminectomy, ETS was 34.1 % ($p < 0.001$) lower than ETS in untreated segments (Table 2; Fig. 2b). Mean ETS was 10.8 Nm/degree (range 4.6–21.9; SD 5.4) in untreated segments and 7.1 Nm/degree (range 1.5–14.3; SD 4.1) in segments with laminectomy. Following laminectomy, LTS was 30.1 % ($p = 0.027$) lower than LTS in untreated segments (Table 2; Fig. 2b). Mean LTS was 5.7 Nm/degree (range 0.6–16.3; SD 5.0) in untreated segments and 4.0 Nm/degree (range 0.8–8.5; SD 2.9) in segments with laminectomy. Segments treated with laminectomy had a significantly lower TMF (17.6 %; $p = 0.041$) than untreated segments (Table 2; Fig. 2b). Mean TMF was

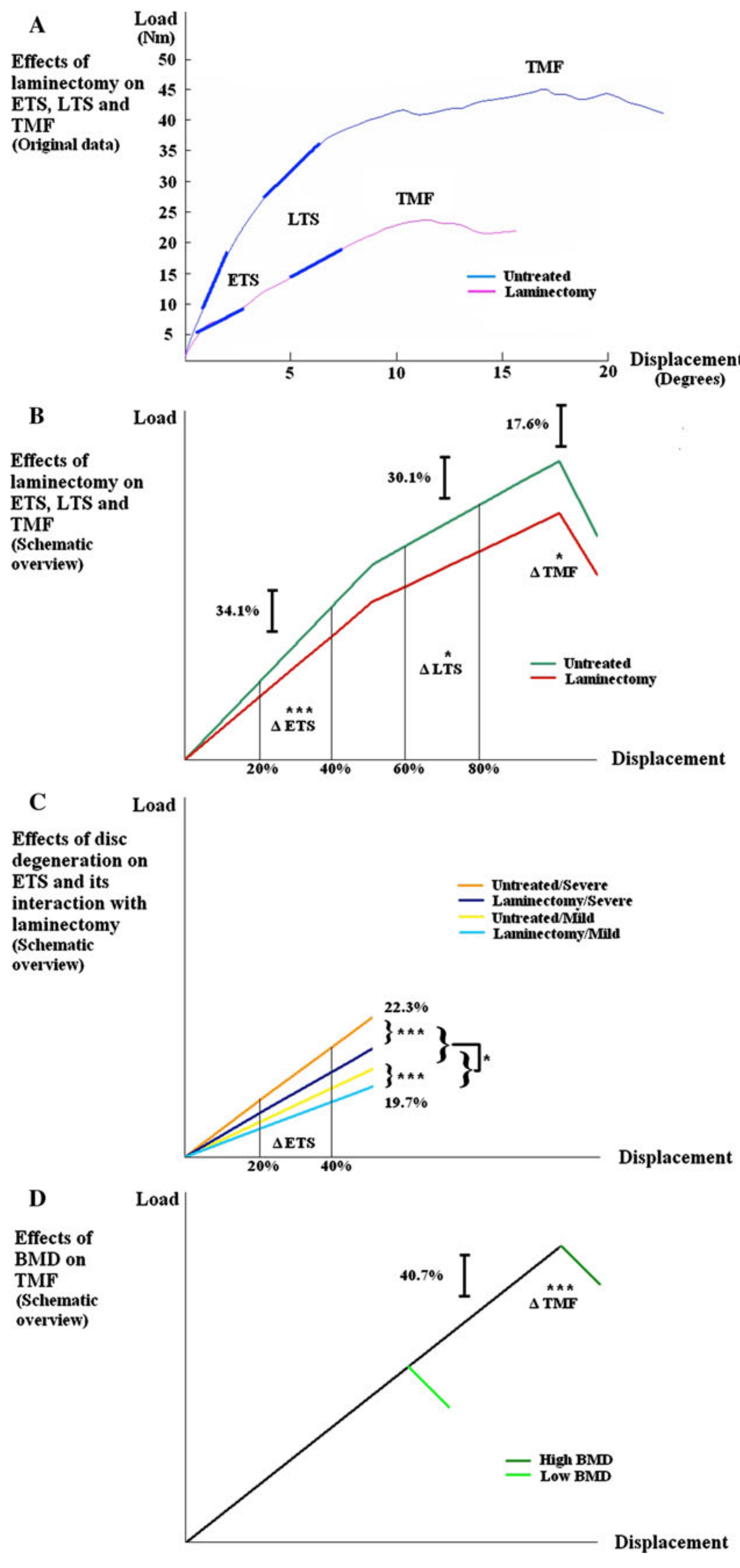

Fig. 2 **a** Typical example of a load–displacement curve showing the significant effects of laminectomy on early torsion stiffness (ETS; between 20–40 % of TMF), late torsion stiffness (LTS; between 60–80 % of TMF) and torsion moment to failure (TMF). The transition phase between the ETS and LTS usually reflected gradual yielding (between 40 and 60 %). In this specific example, the gradual decline in stiffness is more pronounced in the load–displacement curve of the untreated segment, than it is in the load–displacement of the treated segment. **b** Schematic illustration of a load–displacement curve showing the significant effects of laminectomy on early torsion stiffness (ETS; between 20 and 40 % of TMF), late torsion stiffness (LTS; between 60 and 80 % of TMF) and torsion moment to failure (TMF). **c** Schematic illustration of a load–displacement curve, showing the significant effects of disc degeneration on ETS and its significant interaction with laminectomy. **d** Schematic illustration of a load–displacement curve, showing the significant effects of BMD on TMF

Table 2 *P* values for the effects of laminectomy, as well as the effects of disc degeneration (Pfirrmann) and its interactions with laminectomy on torsion moment to failure (TMF), and early torsion stiffness (ETS; between 20 and 40 % of TMF) and late torsion stiffness (LTS; between 60 and 80 % of TMF), based on ANOVA

	Laminectomy	Disc degeneration (Pfirrmann) Mild: 0 (1–3) Severe: 1 (4,5)	Disc degeneration (Pfirrmann) Mild: 0 (1–3) Severe: 1 (4,5) × Laminectomy	Bone mineral density (BMD) High: 0 (≥0.76 g/cm^2) Low: 1 (<0.76 g/cm^2)	Bone mineral density (BMD) High: 0 (≥0.76 g/cm^2) Low: 1 (<0.76 g/cm^2) × Laminectomy
ETS (Nm/degree)	**<0.001**	**<0.001**	**0.031**	0.133	0.486
LTS (Nm/degree)	**0.027**	0.065	0.104	0.111	0.665
TMF (Nm)	**0.041**	0.315	0.990	**<0.001**	0.305

In addition, in the middle 2 columns the effects of BMD and its interaction with laminectomy are presented

Bold values indicate statistical significance at $P < 0.05$

51.4 Nm (range 27.8–79.2; SD 14.7) versus 42.4 Nm (range 23.7–72.5; SD 17.5) following laminectomy.

Effects of disc degeneration on torsion biomechanics

Segments with severe disc degeneration had a significantly higher ($p < 0.001$) ETS than segments with mild disc degeneration (Table 2; Figs. 2c and 3). For ETS, an interaction effect ($p = 0.031$) between disc degeneration and laminectomy was also found (Table 2; Figs. 2c and 3). Mean ETS in severely degenerated specimens was 12.1 Nm/degree (range 4.6–21.9; SD 6.0) in untreated segments versus 9.4 Nm/degree (range 5.6–14.3; SD 4.5) following laminectomy, equivalent to a reduction of 22.3 %. Mean ETS in the mildly degenerated group was 7.6 Nm/degree (range 6.4–8.4; SD 1.0) in the untreated segments and 6.1 Nm/degree (range 1.5–10.3; SD 3.8) in the treated segments, representing a reduction of 19.7 %. Note that effects of laminectomy in severely and mildly degenerated spines were smaller than in the group as a whole. This was due the fact that in the untreated group, specimens were somewhat more degenerated and degeneration did affect ETS. Considering the interaction between the effect of disc degeneration and laminectomy, it was found that the reduction of ETS following laminectomy was larger in severely degenerated discs (mean 2.7 Nm/degree or 22.3 %) than in mildly degenerated discs (mean 1.5 Nm/degree or 19.7 %). LTS was similarly affected by disc degeneration as ETS (Fig. 3). However, neither the main effect of disc degeneration ($p = 0.065$) nor its interaction with laminectomy ($p = 0.104$) reached significance (Table 2). TMF was not affected by disc degeneration nor its interaction with laminectomy (Table 2; Fig. 3).

Effects of BMD on torsion biomechanics

Neither the main effect of low BMD nor its interaction with laminectomy did affect ETS and LTS (Table 2; Fig. 4). TMF was significantly ($p < 0.001$) higher for segments with high BMD than for segments with low BMD (Table 2; Figs. 2d and 3). For TMF, no interaction effect between BMD and laminectomy was found (Table 2; Fig. 4). In the high BMD group, mean TMF was 58.9 Nm (range 43.8–79.2; SD 12.1) versus a mean of 34.9 Nm (range 23.7–51.2; SD 10.0) in the low BMD group, representing a reduction of 40.7 %.

Discussion

In this study, we investigated the impact of lumbar laminectomy on both torsion stiffness (TS) and TMF, and their interaction with disc degeneration and BMD.

Torsional strength of the untreated lumbar spine was studied previously [2, 9, 11]. For untreated lumbar segments, we found an average TMF of 51.4 Nm, which is about twice as high as the average moment to failure reported by Adams and Hutton [2]. These differences are most likely related to both the higher axial compression load and the free rotation center in our study. Adams and Hutton used a fixed rotation center and substantially lower axial compression loads. Furthermore, we used the ultimate force while Adams and Hutton used the yield force. Farfan et al. [9, 11] measured TMF under compression (maximum of 573 N) in degenerated segments; their results were comparable to the present results. We used a constant compressive load level of 1,600 N to allow for comparison with the load levels found in daily physiological loading [16] and to compare with previous work [5, 6]. While this force may seem high, it is not very high compared to that estimated in vivo compression. Mainly due to muscle forces, the spine is already subjected to forces of this magnitude when the trunk is inclined about 45° forward. When lifting a 10 kg object from ground level, compression forces can increase up to about 5,000 N [16]. Failure compressive loads in human cadaveric spines are on average 3,000 N [7]. To facilitate comparison with

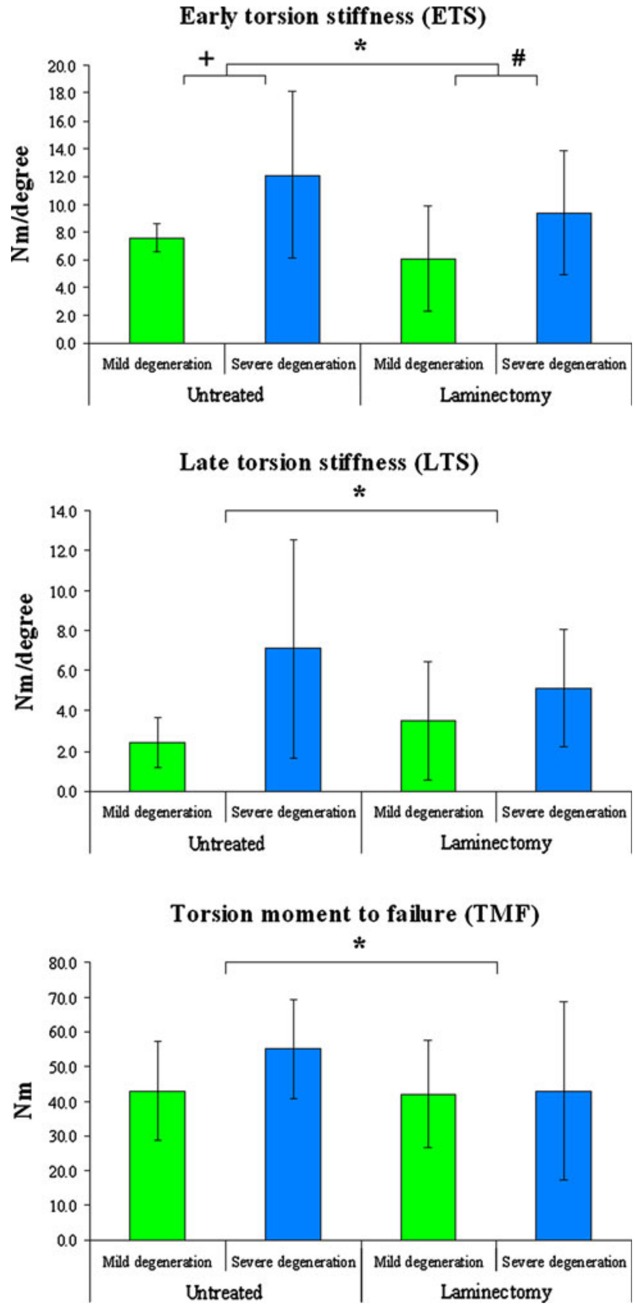

Fig. 3 The effect of laminectomy and disc degeneration on ETS, LTS and TMF (mean values ± SD). Significant differences between untreated and segments with laminectomy are marked (*asterisk*). Significant effects of disc degeneration (*plus symbol*) and its interaction with laminectomy (*hash symbol*) are also marked

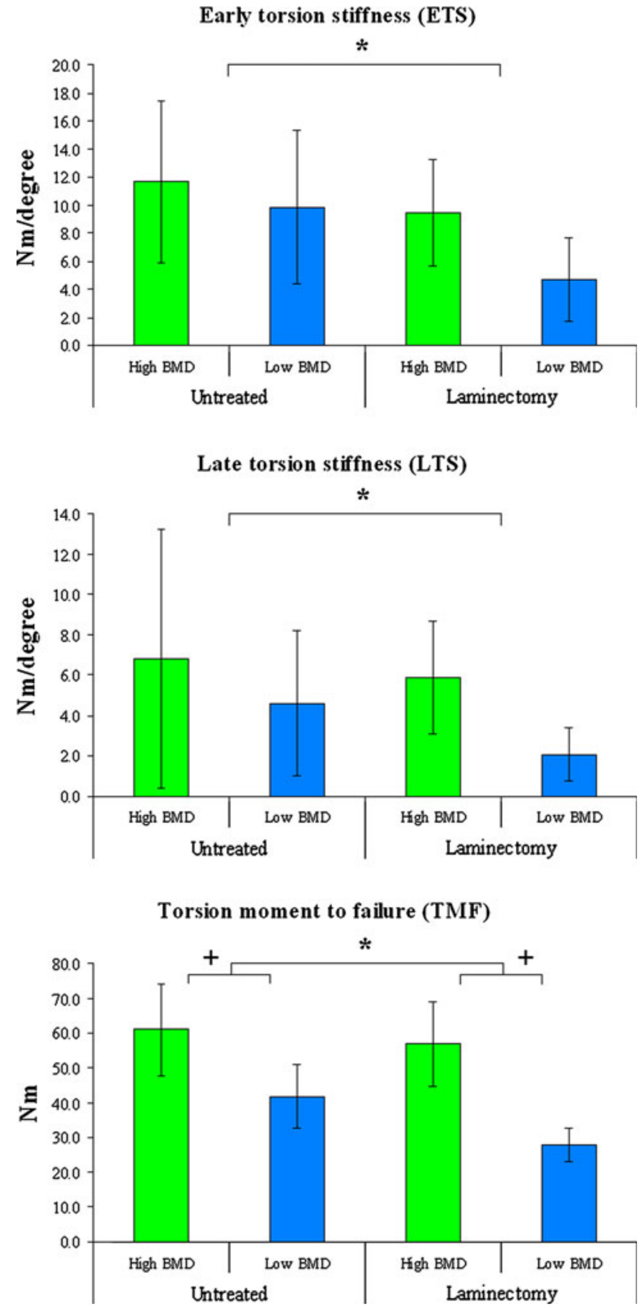

Fig. 4 The effect of laminectomy and BMD on ETS, LTS and TMF (mean values ± SD). Significant differences between untreated and segments with laminectomy are addressed (*asterisk*). Significant effects of BMD are also marked (*plus symbol*)

physiologic loading conditions, spinal segments were tested without imposing a specific axis of axial rotation. Therefore, segments were able to find their physiological motion patterns irrespective of possible differences in embedding. Furthermore, we used a single loading cycle. Cyclic loading might, through visco-elastic behavior of the intervertebral disc, shift load to the posterior element [22], thereby possibly enhancing the detrimental effect of laminectomy on torsional strength. In addition, it should be noted that a limitation of our study is that we used only one specific, relatively low deformation rate (3.0° per min), which might have induced some creep behaviour, effectively transferring rotational resistance from soft tissues to bony structures. However, those effects are likely small.

Busscher et al. [8] found a 10 % increase in axial rotation ROM after 30 min of creep, whereas in the present study TMF was reached within a few minutes in most specimens (Table 1).

We showed that laminectomy reduces TMF and TS of lumbar spinal segments by approximately 18 %, and 34 and 30 % for ETS and LTS, respectively. For shear loading, reductions in strength were larger (44.2 %), while reductions in stiffness were smaller (19.9 %) [5, 6]. Reductions of these biomechanical parameters were expected since posterior elements, consisting of both soft and bony tissue, are crucial in restraining axial rotation [2, 3, 13].

New in our study was that load–displacement curves of torsion biomechanics showed a bi-phasic pattern, with differences between stiffness in the early phase of the load–displacement curve and in the late phase of the load–displacement curve before failure (Fig. 2a, b). Therefore, we differentiated results between ETS and LTS to separately quantify stiffness in the early and late phase of the load–displacement curve. To our best knowledge, this bi-phasic phenomenon was not described previously. We found significant differences ($p < 0.001$) between early and late TS of the human lumbar spine. The transition zone between ETS and LTS possibly indicates yielding. Yielding refers to a decrease in stiffness, possibly reflecting the first damage to the structure [20]. Since the yield-phase in the load–displacement curves did not show a well-defined transition between ETS and LTS, we could not define a yield point. We did not report axial rotation angles at failure. Figure 2a shows a typical example of data, presenting the load–displacement curve of an untreated segment. The 'flat' second part of the curve means that large changes in axial rotation angles can occur, without much change in torsion moment. Therefore, axial rotation angles at failure are unreliable. Concerning the failure patterns during testing, we were, unfortunately, not able to address the exact cause of failure.

It has been reported that the average torque at failure for degenerated discs is lower than for normal discs [11]. Our results did not corroborate this finding. However, we demonstrated a marked effect on ETS, which proved to be approximately 30 % higher in severely degenerated segments in comparison to mildly degenerated treated and untreated segments. In addition, the negative effect of laminectomy on ETS was marginally larger in severely degenerated discs (mean 2.7 Nm/degree) in comparison to mildly degenerated discs (mean 1.5 Nm/degree). As expected, an interaction between disc degeneration and laminectomy was found, since laminectomy causes a shift in load-bearing from the posterior elements to anterior elements [14]. Notably, spinal segments treated with laminectomy and in the presence of severe intervertebral disc degeneration were still found to be stiffer than untreated mildly degenerated segments. This may reflect that severe degeneration makes the disc stiffer in torsion. Alternatively, the increased stiffness with degeneration may reflect increased facet contact in degenerated specimens [19] or direct contact of other structures, such as the endplates. Three segments were severely degenerated (Pfirrmann grade 5) and especially in these segments, results might have been affected by endplate engagement. We performed data analysis again after excluding these segments and indeed the interaction effect between ETS and degeneration disappeared after omitting these segments, while other statistical results did not change. In contrast to stiffness, we found that TMF was not affected by disc degeneration. So a stiffer intervertebral joint does not increase the failure load in torsion, which is probably due to the fact that failure occurs in the bony rather than the intervertebral disc structure.

BMD was found to have a major impact on torsion strength of spinal segments following laminectomy. The effect of low segmental BMD on TMF was even larger than the effect of laminectomy on TMF. These results were consistent with previous findings on shear strength [5, 6] and compressive strength [7, 20]. Significant effects of BMD on stiffness could not be established. Stiffness might be determined by soft tissue primarily. In addition, large standard deviations (Fig. 4) might also have prevented detection of such effects. A limitation is that BMD of dissected lumbar spines is significantly lower than BMD measured in intact human cadavers [21]. However, the absolute differences were small. Previously presented BMD of dissected lumbar spines was slightly higher than our BMD; however, these specimens were substantially younger [15].

Decompressive lumbar laminectomy for severe degenerative spinal stenosis usually leads to a significant postoperative relief of symptoms. Despite these good clinical results, however, some patients present themselves with recurrence of symptoms and unremitting low back pain in the long term. Radiological assessment of these patients does not show evident changes on static and dynamic radiographs, MRI or CT imaging. We hypothesize that these symptoms are a result of a post-operative change in spinal biomechanics. Yielding, i.e., passing the transition zone between ETS and LTS, may be correlated to the recurrence of symptoms. Further studies on the yielding of this typical bi-phasic stiffness of the lumbar spine are necessary. Besides defining a yield point, it could be valuable to determine what biomechanical change causes a spinal segment to yield. Factors determining the yield point and segmental stiffness were already determined for shear loading [6]. Future research should focus on the prognostication of torsion biomechanics after laminectomy.

In conclusion, laminectomy affects both torsion stiffness and torsion load to failure. In addition, torsional strength is strongly affected by BMD whereas disc degeneration affects torsional stiffness. Assessment of disc degeneration and BMD pre-operatively improves the understanding of the biomechanical effects of a lumbar laminectomy.

Conflict of interest None.

References

1. Abel MS (1989) Transverse posterior element fractures associated with torsion. Skeletal Radiol 17:556–560
2. Adams MA, Hutton WC (1981) The relevance of torsion to the mechanical derangement of the lumbar spine. Spine (Phila Pa 1976) 6:241–248
3. Adams MA, Hutton WC (1983) The mechanical function of the lumbar apophyseal joints. Spine (Phila Pa 1976) 8:327–330
4. Adams MA, Roughley PJ (2006) What is intervertebral disc degeneration, and what causes it? Spine (Phila Pa 1976) 31: 2151–2161
5. Bisschop A, Mullender MG, Kingma I, Jiya TU, van der Veen AJ, Roos JC, van Dieen JH, van Royen BJ (2011) The impact of bone mineral density and disc degeneration on shear strength and stiffness of the lumbar spine following laminectomy. Eur Spine J 21:530–536
6. Bisschop A, van Royen BJ, Mullender MG, Paul CP, Kingma I, Jiya TU, van der Veen AJ, van Dieen JH (2012) Which factors prognosticate spinal instability following lumbar laminectomy? Eur Spine J 21:2640–2648
7. Brinckmann P, Biggemann M, Hilweg D (1989) Prediction of the compressive strength of human lumbar vertebrae. Spine (Phila Pa 1976) 14:606–610
8. Busscher I, van Dieen JH, van der Veen AJ, Kingman I, Meijer GJM, Verkerke GJ, Veldhuizen AG (2011) The effects of creep and recovery on the in vitro biomechanical characteristics of human multi-level thoracolumbar spinal segments. Clin Biomech (Bristol, Avon) 26:438–444
9. Farfan HF (1969) Effects of torsion on the intervertebral joints. Can J Surg 12:336–341
10. Farfan HF (1984) The torsional injury of the lumbar spine. Spine (Phila Pa 1976) 9:53
11. Farfan HF, Cossette JW, Robertson GH, Wells RV, Kraus H (1970) The effects of torsion on the lumbar intervertebral joints: the role of torsion in the production of disc degeneration. J Bone Joint Surg Am 52:468–497
12. Gordon SJ, Yang KH, Mayer PJ, Mace AH Jr, Kish VL, Radin EL (1991) Mechanism of disc rupture. A preliminary report. Spine (Phila Pa 1976) 16:450–456
13. Gunzburg R, Hutton WC, Crane G, Fraser RD (1992) Role of the capsulo-ligamentous structures in rotation and combined flexion-rotation of the lumbar spine. J Spinal Disord 5:1–7
14. Haher TR, O'Brien M, Felmly WT, Welin D, Perrier G, Choueka J, Devlin V, Vassiliou A, Chow G (1992) Instantaneous axis of rotation as a function of the three columns of the spine. Spine (Phila Pa 1976) 17:149–154
15. Hans D, Barthe N, Boutroy S, Pothuaud L, Winzenrieth R, Krieg MA (2011) Correlations between trabecular bone score, measured using anteroposterior dual-energy X-ray absorptiometry acquisition, and 3-dimensional parameters of bone microarchitecture: an experimental study on human cadaver vertebrae. J Clin Densitom 14:302–312
16. Kingma I, Bosch T, Bruins L, van Dieen JH (2004) Foot positioning instruction, initial vertical load position and lifting technique: effects on low back loading. Ergonomics 47:1365–1385
17. Kingma I, van Dieen JH, de Looze M, Toussaint HM, Dolan P, Baten CT (1998) Asymmetric low back loading in asymmetric lifting movements is not prevented by pelvic twist. J Biomech 31:527–534
18. Pfirrmann CW, Metzdorf A, Zanetti M, Hodler J, Boos N (2001) Magnetic resonance classification of lumbar intervertebral disc degeneration. Spine (Phila Pa 1976) 26:1873–1878
19. Pollintine P, Przybyla AS, Dolan P, Adams MA (2004) Neural arch load-bearing in old and degenerated spines. J Biomech 37: 197–204
20. Renau A, Farrerons J, Yoldi B, Gil J, Proubasta I, Llauger J, Olivan JG, Planell J (2004) Yield point in prediction of compressive behavior of lumbar vertebral body by dual-energy X-ray absorptiometry. J Clin Densitom 7:382–389
21. Tan JS, Kayanja MM, St Clair SF (2010) The difference in spine specimen dual-energy X-ray absorptiometry bone mineral density between in situ and in vitro scans. Spine J 10:784–788
22. van Dieen JH, van der Veen A, van Royen BJ, Kingma I (2006) Fatigue failure in shear loading of porcine lumbar spine segments. Spine (Phila Pa 1976) 31:494–498